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Consequence analysis of large-scale liquefied natural gas spills on water

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1. Introduction

1.1 Background

As public concerns increase over global warming caused by the burning of fossil fuels, natural gas is gaining a lot of attention for the lowest emission of carbon dioxide among the fossil fuels. Thus, governments implementing national or regional plans to reduce greenhouse gas emissions may encourage its use to displace other fossil fuels. According to the Energy Information Administration, the worldwide natural gas consumption in 2030 will increase by about one and a half times as much as in 2006 (EIA, 2009), so that the number and frequency of seaborne transportation of liquefied natural gas (LNG) are expected to increase significantly around the world. In fact, there are a lot of projects to build new receiving terminals in the United States. Also, natural gas consumption is expected to rise rapidly in China and India. With such a growing global demand, recent LNG carriers (LNGCs) become larger up to a 266,000 m³ cargo capacity, which are referred to as Q-Max vessels.

Due to the above change in the situation, there has recently been considerable interest concerning possible risks involved in the LNG carrier operations, though seaborne transportation of LNG has been conducted with a very good safety record since 1959. Hence, public authorities have raised their awareness of concern about the possibility of large-scale LNG spill hazards caused by accidental events or intentional attacks. As a result, a number of consequence analyses have been carried out in recent years in order to propose models and approaches or to assess hazards resulting from an unconfined LNG spill over water (Luketa-Hanlin, 2006). However, these studies showed a broad range of results due to their differences in models, approaches and assumptions, since the physics involved in such LNG spills and related phenomena is very complicated. In addition, because of the lack of experimental data for a large-scale LNG spill and subsequent combustion and/or dispersion events, there are many theoretical and experimental gaps related to understanding of the dynamics and limitations in predicting the associated hazards. Therefore, consequence assessment methods based on a combination of theoretical formulations and empirical relationships derived from laboratory and small-scale field experiments are the only practical measure to predict the hazards associated with large-scale LNG spills on water.

On the other hand, a broad range of results of these studies indicates how important it is to use appropriate assumptions, data, and models in trying to make an accurate assessment of hazards from an LNG spill. Although the results of recent consequence studies were compared in a few publications (Hightower et al., 2004), there was no comparison study on consequence models under the same scenarios in terms of LNG properties, release assumptions and weather conditions. Therefore, the current author compared and evaluated consequence models for pool fire hazards involving an LNG spill on water in order to clarify their characteristics (Oka & Ota, 2008).

In the above comparison study, attention was paid to thermal radiation hazards from pool fires, because there is a high possibility that an ignition source immediately after breaching a tank will be available (Hightower et al., 2004). Hence, the sensitivity analysis of a spill and the subsequent pool fire hazards to the hole size breached in a membrane-type tank of a conventional size LNGC (125,000 m³ cargo capacity) were carried out using three major consequence assessment methods developed by the Federal Energy Regulatory Commission (FERC) (FERC, 2004), Sandia National Laboratories (SNL) (Hightower et al., 2004) and Fay (Fay, 2003). These methods were chosen based on an in-depth review of the recent literature available to the public. Through the sensitivity analysis, it was found that the FERC method was most appropriate for practical consequence analyses of incidents involving large-scale LNG spills on water from the practical viewpoint of applicability to any breach size.

Recent LNGCs are designed to have as much as a 266,000 m³ cargo capacity, so that it is important to evaluate how much the extent of the hazard impact would increase due to the enlarged size and capacity of such carriers. Thus, thermal radiation hazards from pool fires involving spills from one of the latest and largest LNGCs (250,000 m³ cargo capacity) were assessed using the recommended FERC method, and the results were discussed in comparison with those for the conventional size LNGC. As a result, it was found that the maximum thermal hazard distance was only about 24 % longer than that for the conventional LNGC, while the spill volume was twice as much (Oka & Ota, 2008).

When the author focused on estimating LNG spill hazards from the latest LNGC, similar hazard assessments had not been covered at least in the publicly available literature. However, in almost the same period the U.S. Department of Energy requested that SNL conduct analyses of possible spill hazards from a breach of the latest LNGC (Luketa et al., 2008). The results of both studies were published at the same time. This updated SNL study presented somewhat different results in that the thermal hazard distances increased by approximately 7–8 % due to the increase in hydrostatic head and tank volume for the new, larger LNGC. In the scenarios used in the SNL studies (Luketa et al., 2008), the nominal breach size and the total spill volume from a single tank were determined as 5 m² and 41,000 m³, respectively, so that a smaller breach size and a larger spill volume were used than those in the other study (Oka & Ota, 2008). Hence, for quantitative comparison, the current author carried out consequence analyses of pool fire hazards following an LNG spill from a breached tank of the conventional and latest LNGCs under the same scenarios as in the SNL studies (Oka, 2009). It was found that, as a whole, the thermal hazard consequences by the SNL method were in fairly good agreement with those by the FERC method.

1.2 Scope of the present study

The principal LNG hazards of interest for the present study are those posed by thermal radiation and flammable vapor dispersion resulting from unconfined LNG spills on water.

Cryogenic burns and asphyxiation are typically localized to LNG transport and storage areas, so that such secondary hazards are outside the scope of this study.

The two previous studies for the latest LNGC by the FERC method (Oka & Ota, 2008; Oka, 2009) were carried out under the following scenarios. In the first study (Oka & Ota, 2008), predicted consequences were compared only when the hole diameters were 1, 3 and 5 m as typical hole sizes, which were chosen from the recent literature on the assessment of the impacts of large-scale release from the conventional type LNGC. In the second study (Oka, 2009), two breach sizes of 5 and 12 m² were used as nominal tank breaches for near-shore and offshore LNG marine import operations, respectively, so as to compare the updated SNL study (Luketa et al., 2008). Therefore, no sensitivity analysis of pool fire hazards to the hole size has been carried out for the latest LNGC.

As for flammable vapor dispersion hazards, as far as the author knows, there is no study to assess consequences predicted by the FERC method for the latest LNGC. Though the sensitivity analysis of spills and the subsequent dispersion hazards to the breach size were conducted for the conventional size LNGC using the FERC method (Qiao et al., 2006), the averaging time used to estimate flammable gas concentrations was much larger than the recommended value in the FERC method. Thus, it is interesting to evaluate the sensitivity using the FERC method composed of all the recommended models and assumptions for the latest LNGC.

The present work considers the sensitivity of the flammable vapor and thermal radiation hazards to the hole diameter under release scenarios that a hole can develop just above the waterline level in the event of a breach of a single tank on the conventional and latest LNGCs. Under current circumstances, from the practical viewpoint of applicability to any breach size, the FERC method has been recommended in the previous studies (Oka & Ota, 2008; Oka, 2009), so that the present consequence analyses are carried out using the same method.

2. Overview of potential consequences

Currently, the potential for the dynamics and dispersion of a large spill and the associated hazards are not fully understood. As will be shown in Fig. 1 later, existing experimental data on LNG spill dynamics, dispersion, and burning over water cover only small amount of spill volumes that are two to three orders of magnitude less than those postulated in the recent literature (Luketa-Hanlin, 2006).

2.1 Brief description on major hazards of an LNG spill on water

The potential hazards associated with LNG spills include cryogenic damage caused by direct contact, pressure increase due to rapid phase transition (RPT), flash fires, pool fires, deflagrations and detonations. Because of its extremely low temperature, direct contact with LNG will result in brittle fracture of the ship's structure, which may cause cascading damage to additional LNG tanks. When LNG comes in contact with water at a significantly higher temperature than the boiling point of LNG, there is the possibility of RPT, which is a nearly instantaneous transition from the liquid to vapor phases and produces an associated rapid pressure increase. The impacts of RPT will be localized near the spill source and should not cause extensive structural damage.

LNG is comprised mostly of methane, so that LNG vapor is flammable in air approximately at 5 to 15 % by volume. At a 5 % concentration of gas in air, LNG vapor is at its lower flammability limit (LFL). Below the LFL, the cloud is too dilute for ignition. At a 15 % concentration of gas in air, LNG vapor is at its upper flammability limit (UFL), so that the cloud is too rich in LNG for ignition above the UFL.

The evaporating natural gas in the above range of combustible gas-air concentrations will burn above the LNG pool when it ignites immediately after LNG release. The resulting pool fire would spread as the LNG pool expands away from its source and continues evaporating. If released LNG does not ignite immediately, the LNG will form a vapor cloud that may drift some distance from the spill site at roughly the wind speed. Once it warms above approximately -108°C , LNG vapor will become less dense than air and tend to rise and disperse more rapidly. However, LNG vapor at its normal boiling point -162°C is 1.5 times denser than air at 25°C . Typically, LNG vapor released into the atmosphere will remain negatively buoyant until after it disperses below its LFL. Therefore, the displacement of air by LNG vapor may cause asphyxiation as well as lung damage from breathing the cold vapor.

In the case of delayed ignition at downwind locations to which the spill vapor might spread, a flash fire will occur. This is a short duration fire that burns the vapor already mixed with air to flammable concentrations. The flame front may burn back through the vapor cloud to the spill site, resulting in a pool fire. A flash fire will burn slowly and is unlikely to generate damaging overpressures when it occurs in an unconfined space.

Explosions arising from combustion of flammable fuel-air mixtures are classified as either a detonation or a deflagration. Detonations generate very high overpressures, and hence are more damaging than deflagrations. It is pointed out that weak ignition of natural gas vapor in an unconfined and unobstructed environment is highly unlikely to result in deflagration-to-detonation transition (DDT). This transition is more likely in an environment with confinement such as with closely spaced obstacles, so that damaging overpressures could result from explosions in a confined space in cases that the flammable vapor leaks into a confined space inside LNGCs or other congested structures and then ignites.

2.2 Review of experiments on large-scale LNG spills

This subsection briefly reviews experiments on the vapor dispersion, pool fire and vapor cloud fire which are formed from unconfined LNG spills onto water. In reference to recent review papers (Luketa-Hanlin, 2006; Koopman & Ermak, 2007; Raj, 2007), only the largest spill volume tests are outlined chronologically in the following.

In 1973, the Esso Research and Engineering Company and the American Petroleum Institute carried out LNG dispersion tests in Matagorda Bay, Texas (Feldbauer et al., 1972). Volumes ranging from 0.73 to 10.2 m^3 were spilled. Pool radii ranging from 7 to 14 m were visually observed, and visible vapor clouds were very low in height compared to their lateral extent. In 1978, the U.S. Coast Guard China Lake tests (Schneider, 1980) were performed at the Naval Weapon Center (NWC) in China Lake, California in order to measure the thermal radiation output of pool fires as well as vapor cloud fires. The volumes of LNG ranged from 3 to 5.7 m^3 were released towards the middle of an unconfined water surface of a pond. The effective pool diameter was up to 15 m, and the flame lengths ranged from 25 to 55 m. In 1980, Shell Research conducted a series of experiments at Maplin Sands in England to obtain dispersion and thermal radiation data for 20 spills of 5 to 20 m^3 of LNG on the surface of the

sea (Blackmore et al., 1982; Mizner & Eyre, 1983). An effective pool diameter of 30 m was calculated by approximating the flame base area as an ellipse. A pool fire was formed in one test, but it continued only for a few seconds before the fuel was consumed. Therefore, a fully developed pool fire was not achieved. At the same time as the Maplin Sands tests, the Burro series tests were conducted independently by the Lawrence Livermore National Laboratory (LLNL) at NWC (Koopman et al., 1982). The main objective of the Burro series was to obtain extensive data on LNG vapor dispersion under a variety of meteorological conditions. A total of eight LNG release onto water were performed with spill volumes ranging from 24 to 39 m³. The pool radius measured in the tests was up to 5 m. The Coyote series tests (Rodean et al., 1984) followed the Burro series in 1981 so as to measure the characteristics of large vapor cloud fires and obtain more dispersion data from LNG spills ranging from 14.6 to 28 m³ onto water. It was observed that the flame propagated toward the spill source and subsequently a pool fire occurred. However, measurements were not taken in the experiment of the flame propagation. After the Burro and Coyote series, the Falcon series tests (Brown et al., 1990) were conducted by LLNL in 1987. The main goal of the experiments were to provide a database on LNG vapor dispersion from spills in an environment with obstacles and to assess the effectiveness of vapor fences for mitigating dispersion hazards. The Falcon tests have been the largest spills so far, with release rates up to 30 m³/min and spill volumes ranging from 21 to 66 m³.

Figure 1 shows a comparison of the spill sizes tested to date with possible spill volume from a single LNG cargo tank through a hole just above the waterline level. It can be seen from this figure that the experimental tests were performed on considerably smaller scales compared with an LNGC tank size. In other words, there is a large disparity between the available experimental data and the scales of interest for consequence assessments, so that there are gaps and limitations in understanding and predicting the hazards associated with large-scale spills from a cargo tank. Therefore, a lot of consequence assessment methods for practical use can provide only rough estimates of the magnitude of effects for incidents involving large LNG release on water.

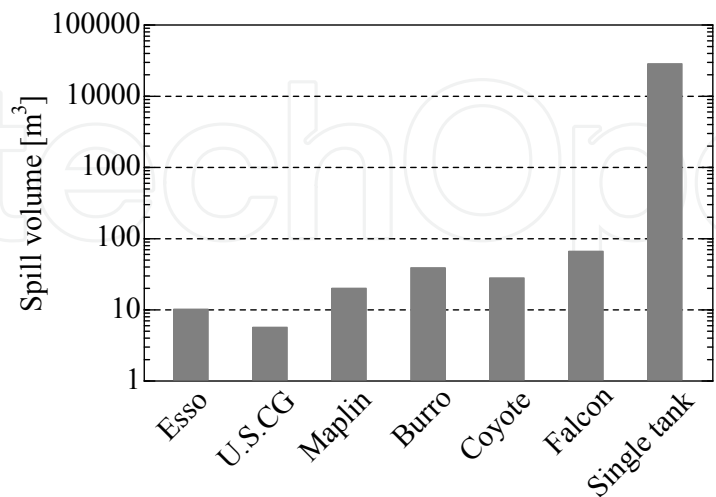


Fig. 1. Logarithmic scale comparison of spill volume level in field experiments with that of a possible cargo spill from a single tank of the latest LNGC.

3. Consequence assessment methods

In almost all of the studies on consequence modeling of LNG spill hazards, it is assumed that the reference LNGCs have membrane tanks. Qiao et al. investigated the influence of the geometric difference between membrane and Moss spherical tanks on the LNG release rate from a hole, but they did not carry out consequence analyses under the condition that LNG was released from a Moss spherical tank (Qiao et al., 2006). Hence, a membrane type LNGC is adopted as a reference vessel in accordance with the majority of studies. For the purpose of consequence assessment modeling, the geometry of a membrane tank is much simplified to a rectangular box, as shown in Fig. 2. Though an LNGC has a complete double hull in reality, a single hull structure is assumed on the side of the reference LNGC. The reason of this assumption will be described later.

The consequence analyses of LNG spill hazards are conducted in the following steps:

1. Calculate the LNG release rate from a non-pressurized tank with a single hole,
2. Calculate the diameter of the volatile liquid pool spreading on water,
3. In the scenario of immediate ignition, calculate the size of a pool fire and distances to specified radiative flux levels of concern. Otherwise, skip to the next step,
4. In the case of delayed or remote ignition, calculate downwind dispersion distances to specified concentration levels of concern.

Consequence models in each step, which constitute a consequence assessment method, are described in the following subsections.

3.1 LNG release from a cargo tank of a ship

In the absence of appropriate models that account for the complex structure of an LNGC and the physics of release of cryogenic LNG, a simple orifice model is employed in the FERC method on the assumption of a single hull structure of an LNGC. In spite of the complete double hull structure in reality, the orifice model is widely used even in the recent literature on consequence assessment (Luketa-Hanlin, 2006). Since this model assumes release from a single hole on the side of a ship with single hull structure, LNG flows directly from a tank onto the seawater without any leakage into the space between hulls.

The release rate from the tank to the seawater is expressed as a function of height through invoking Bernoulli's equation. Multiplied by a discharge coefficient, the mass flow rate is expressed as follows:

$$\dot{M} = C_d \rho_l \pi R^2 \sqrt{2gh} \quad (1)$$

where \dot{M} is the mass flow rate, C_d is the discharge coefficient to take account of the resistance given by the hole, ρ_l is the LNG density, R is the effective radius of the hull breach, h is the static head above the hull breach, g is the acceleration due to gravity.

Discharge coefficient C_d is often used to account for reduction below the theoretical exit velocity due to viscosity and secondary flow effects. In other words, it depends on the nozzle shape and the Reynolds number. In the case of an ideal frictionless discharge, it is reasonable that C_d is set to unity. In practice, however, a rough, irregular breach could occur in the wall of an LNG cargo tank, so that the friction would be expected to be larger than that in the case of a well-rounded, sharp-edged orifice. Thus, FERC recommended 0.65 as a reasonable estimate to account for the fact that friction retards the flow (FERC, 2004).

The orifice model does not attempt to account for the multi-hull construction of LNGCs, and therefore may overestimate the rate at which LNG would escape through a hole. Hence, the results should be interpreted as a rough guide to the rate of release for a given hole size.

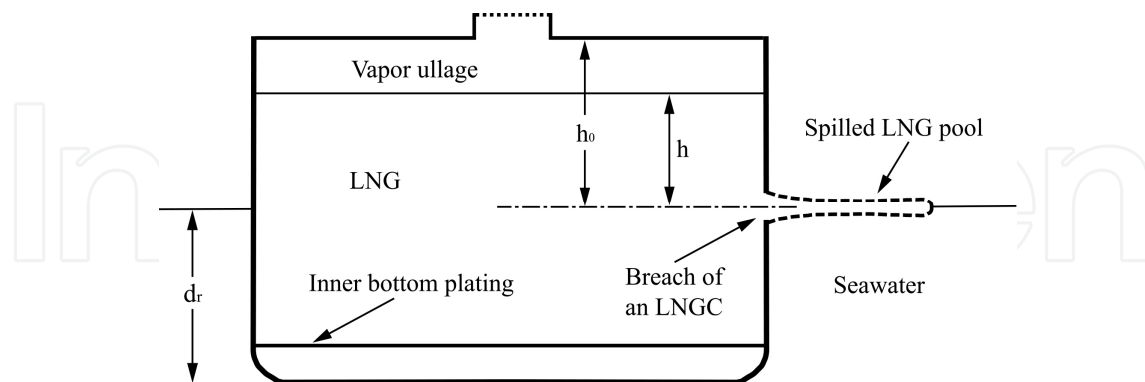


Fig. 2. Schematic view of a cross-section of an LNGC with a hole breached on the side. The amount of LNG just above the waterline is released through the hole over the seawater (Oka & Ota, 2008).

3.2 Spread of an unconfined, evaporating LNG pool on water

LNG spilled on water forms a floating pool because its density is roughly half that of water. This pool will spread over unconfined water, and will vaporize simultaneously due to the high heat transfer from the water and/or other sources. The ABSG study (ABSG, 2004) recommended the use of Webber's model (van den Bosch, 1997) since it has a sound theoretical basis and accounts for friction effects. This model is based on self-similar solutions of the shallow water equations and lubrication theory. In this formulation, resistance by turbulent or laminar friction effects is included in the pool spread equation as follows:

$$\frac{d^2r}{dt^2} = \frac{4\Phi g_r \delta}{r} - C_F, \quad (2)$$

where r is the pool radius, t is the time, δ is the mean depth of the LNG pool, Φ is the dimensionless shape factor that describes the pool thickness profile, and C_F is the turbulent or viscous resistance term. The reduced acceleration due to gravity g_r is defined as follows:

$$g_r = \frac{\rho_w - \rho_l}{\rho_w} g, \quad (3)$$

where ρ_w is the seawater density. In order to close Eq. (2), Webber also provided theoretical and empirical models to determine δ , Φ and C_F (van den Bosch, 1997).

Next, film boiling effects on the above spreading model is briefly described. As an LNG pool spreads on a water surface, the heat transferred from the water and other sources will cause the liquid to vaporize. In the vapor dispersion scenario, vaporization is mainly controlled by heat transfer from the water to the LNG pool. The FERC recommended a film boiling heat

flux of 85 [kW/m²] as a reasonable value, which was obtained in the Burro series tests (Koopman et al., 1982). In the pool fire scenario, vaporization is controlled by heat transfer from both water and fire to the LNG pool. The FERC recommended a mass burning rate per unit area \dot{m}_b as 0.282 [kg/m²/s]. The film boiling and mass burning rates per unit area of the LNG pool are regarded as constant, but the total mass removal rate is dynamically linked to the spreading rate through the pool area.

In the present spread model of an evaporating pool, the physical effects of winds, waves, and currents are not taken into consideration. Several attempts to quantify some of these effects have been made in a few studies (Cornwell & Johnson, 2004; Spaulding et al., 2007), but it is difficult to validate them due to the lack of experimental data. On the other hand, Fay recently showed that the effects of ocean wave interaction on the spread of an evaporating LNG pool were only small or negligible in his classical and newly proposed models (Fay, 2007).

3.3 Thermal radiation from pool fires on water

LNG is known as a clean burning fuel, but significant smoke production is expected for large LNG pool fires (Luketa-Hanlin, 2006). This will tend to obscure the flame and reduce the thermal radiation emitted from the fire. Therefore, the FERC recommends the use of the two-zone solid flame model (Rew & Hulbert, 1996) for assessing the thermal hazards from pool fires. This model assumes that the flame is divided into lower and upper zones. Smoke does not obscure the flame in the lower zone, while it obscures the flame and reduces the amount of thermal radiation emitted from the upper zone. To determine the flame geometry, this model assumes that the flame is a solid, gray emitter having a regular well-defined shape such as an upright or tilted cylinder. The radiative heat flux upon an object can be determined by

$$q = \tau EF, \quad (4)$$

where τ is the atmospheric transmissivity, E is the surface emissive power, and F is the geometric view factor between the target and the cylindrical flame. The view factor F is determined from the dimension of flame area, which is characterized by the flame base diameter, visible flame height, and flame tilt. The flame base is equivalent to the pool size calculated by the pool spread model.

The flame height depends on the flame base diameter and the burning rate, and their correlation was developed by Thomas (Beyler, 2002) as follows:

$$\frac{H}{D} = 55 \left(\frac{\dot{m}_b}{\rho_a \sqrt{gD}} \right)^{0.67} \cdot (u^*)^{-0.21}, \quad (5)$$

where H is the mean visible height of turbulent diffusion flames, D is the effective diameter of a pool, ρ_a is the ambient air density. The FERC method takes the effect of winds into consideration, so that the nondimensional wind speed u^* is determined by

$$u^* = \frac{u_w}{(g\dot{m}_b D / \rho_v)^{1/3}}, \quad (6)$$

where u_w is the wind speed measured at a height of 1.6 m, and ρ_v is the vapor density. However, u^* is assigned a value of unity if it is less than 1.

3.4 Vapor dispersion of LNG spills on water

When considering large release of LNG, dense-gas effects are important and must be taken into consideration in a dispersion model used for analysis. In the FERC method, the DEGADIS model (Spicer & Havens, 1987) was recommended for use in estimating the distances that flammable vapor might reach. DEGADIS accounts for dense-gas effects and was originally developed for the simulation of cryogenic flammable gas dispersion, particularly for LNG. The DEGADIS model are widely used in the public and private sectors due to the convenience of fast computational run time and ease of use. It has been validated against a wide range of laboratory and field test data. Furthermore, the federal siting requirements for onshore LNG facilities (CFR, 1980) specify the use of DEGADIS for the determination of dispersion distances.

DEGADIS is one of one-dimensional integral models which use similarity profiles that assume a specific shape for the crosswind profile of concentration and other properties. The similarity forms represent the plume as being composed of a horizontally homogeneous section with Gaussian concentration profile edges as follows:

$$c(x, y, z) = \begin{cases} c_c(x) \exp \left[-\left\{ \frac{|y| - b(x)}{S_y(x)} \right\}^2 - \left\{ \frac{z}{S_z(x)} \right\}^{1+\alpha} \right] & \text{for } |y| > b(x), \\ c_c(x) \exp \left[-\left\{ \frac{z}{S_z(x)} \right\}^{1+\alpha} \right] & \text{for } |y| \leq b(x), \end{cases} \quad (7)$$

where C is the concentration, C_c is the centerline, ground-level concentration, b is the half width of a horizontally homogeneous central section of gas plume, and S_y and S_z are the horizontal and vertical concentration scaling parameters, respectively. The downwind variations of spatially averaged, crosswind values are determined by using the conservation equations only in the downwind direction of x . Wind velocity u_x is assumed to be based on a power law profile as follows:

$$u_x = u_0 \left(\frac{z}{z_0} \right)^\alpha, \quad (8)$$

where u_0 is the wind speed measured at $z = z_0$, and z_0 is the reference height in wind velocity profile specification. The power coefficient α in Eqs. (7) and (8) is a function of atmospheric stability and surface roughness. In DEGADIS, it is determined by a weighted least-squares fit of the logarithmic profile of wind speed.

Transient denser-than-air gas release cannot be represented as steady, continuous release, so that the spill is modelled as a series of pseudo-steady-state release in DEGADIS. It should be noted that the application of DEGADIS is limited to the description of atmospheric dispersion of denser-than-air gas release at ground level onto flat, unobstructed terrain or water. In other words, the weakness is that it cannot model the flow around obstacles or over complex terrain.

3.5 Summary of Consequence assessment methods

The consequence models for LNG release from a tank, volatile pool spread, thermal radiation from a pool fire, and denser-than-air gas dispersion have been briefly described in the previous subsections. These constitutive submodels in the FERC method are summarized in Table 1. In the pool spread process, its shape is assumed to be semi-circular because of the existence of a ship (Fay, 2003; FERC, 2004). The vaporization due to heat transfer from the fire and/or the water to the pool is taken into consideration, but environmental effects of waves, currents and winds are not incorporated into the spread model.

In general, since many of constitutive submodels for practical use, such as those in the FERC method, have limitations that can cause greater uncertainty in calculating release, spread, and subsequent hazards, these methods can provide only rough estimates of the magnitude of effects for incidents involving large LNG releases on water. The more detailed models based on computational fluid dynamics (CFD) techniques can be applied to improve analysis of site-specific hazards and consequences in higher hazard zones. In the vapor dispersion process, for example, it is important to appropriately represent the topography downwind of the release point so as to obtain precise estimates of effects in actual incident circumstances. However, CFD models have also their own limitations, and its further refinement is required to improve the degree of accuracy and reliability for consequence assessment modeling (Hightower et al., 2005). In addition, due to high computational costs, CFD models are not normally used for practical hazard assessment under the present circumstances.

LNG RELEASE	POOL SPREAD		VAPORI-ZATION	POOL FIRE		VAPOR DISPERSION	
Discharge coefficient	Time evolution	Friction effects included	Vaporization rate [kg/m ² /s]	Flame model	Surface emissive power [kW/m ²]	obstacles or terrain effects included	Averaging time
0.65	Unsteady	Yes	0.282 (Pool fire) ----- 0.17 (Dispersion)	Two-zone solid cylinder that includes tilt for wind effects	265	No	Not more than a few seconds

Table 1. Summary of principal features of the FERC method

3.6 Consequence analysis conditions for LNG spill hazards

Large-scale LNG spill hazard scenarios (Oka & Ota, 2008) are shown in Table 2. These assumptions were originally employed in the ABSG study (ABSG, 2004; FERC, 2004) for the conventional size LNGC except for the total spill volume and the breach size. In the ABSG study, only two holes of 1 and 5 m in diameter were chosen to provide calculation examples of pool fire and vapor dispersion scenarios. In the present study, sensitivity to the breach size is analyzed in the range from 0.5 to 15 m in diameter. Unlike the ABSG study, the spill volume is determined based on Fay's study (Fay, 2003). He simplified the geometry of a membrane tank to a rectangular box and estimated the volume of the spilled LNG as follows. If d_r is the fully-loaded draft, the initial height h_0 (see Fig. 2) of the upper surface of LNG above the waterline level is about $1.1d_r$ for the conventional LNGC. The cargo surface area A_t is related to the cargo tank volume V_{ct} by the following equation,

$$A_t \approx 0.52 \cdot \frac{V_{ct}}{d_r}.$$

(9)

For an LNGC of a 125,000 m³ cargo capacity, with an 11.8 m draft and a 25,000 m³ cargo tank volume, the initial height h_0 and the cargo surface area A_t are estimated to be 13 m and 1,100 m², respectively. Thus, the volume of the spilled LNG from the tank is given as $h_0A_t=14,300$ m³. Meanwhile, the height from the inner bottom plating to the load water line is easily derived from Eq. (9) as $0.82d_r$, so that the depth of a double bottom is $0.18d_r \approx 2.1$ m. This is a typical value for membrane type LNGCs. Therefore, Eq. (9) can be considered as a reasonable expression to easily estimate the typical dimensions of a membrane tank. Hence, the total spill volume for the latest LNGC is also determined in the same manner.

LNG carrier	Conventional	Latest
LNG properties: LNG composition LNG density	Methane 422.5 kg/m ³	
Release assumptions:		
Total cargo capacity	125,000 m ³	250,000 m ³
Volume of a cargo tank	25,000 m ³	50,000 m ³
Total spill volume	14,300 m ³	28,600 m ³
Initial LNG height above breach	13 m	13.2 m
Breach size	0.5 to 15 m in diameter	
Breach location	Just above the waterline	
Pool shape	Semi-circle	

Table 2. Release scenarios for an LNG spill from a tank of the conventional and latest LNGCs

Weather conditions at the time of the release have a major influence on the extent of dispersion. Thus, environmental conditions for the above spill hazard scenarios are provided in Table 3. These conditions were also used in the ABSG study (ABSG, 2004; FERC, 2004). In the vapor dispersion scenario, a wind speed of 2.0 m/s at 10 m above ground and an F stability class were used for an atmospheric stability condition. The F class is extremely stable and the atmospheric turbulence is very weak, so that it takes the greatest amount of

time for the released gases to mix with the atmosphere. In other words, such low wind speed and stable atmospheric condition result in the greatest downwind distance to the LFL. In general, for a lot of one-dimensional integral models, topography is characterized by the surface roughness value. Since the surface roughness accounts for the effects of terrain on the vapor dispersion, a rougher surface will tend to cause more mixing with ambient air, which results in more rapid dispersion of a vapor cloud. As for the averaging time of gas concentration, the FERC method recommended that a short averaging time (not more than a few seconds) be used because a flammable cloud need only be within the flammable range for a very short time to be ignited. In the ABSG scenario (ABSG, 2004; FERC, 2004), its averaging time was set to 0 second, that is, a peak concentration was used.

Hazards	Pool fire	Vapor dispersion
Air temperature	300 K	295 K
Water temperature	294 K	294 K
Relative humidity	70 %	50 %
Wind speed	8.9 m/s	2.0 m/s
Pasquill stability class	-	F
Surface roughness	-	0.01 m

Table 3. Environmental conditions for the scenarios of pool fire and vapor dispersion hazards

4. Results and discussion

This work considers thermal radiation and flammable vapor hazards caused by unconfined LNG spills on water resulting from an LNG cargo release. The recommended FERC method is used to analyze the sensitivity of the LNG hazard consequences to the breach diameter in the following subsections. Based on the physical models and numerical algorithms of the FERC method, a computer program written in the Fortran 90 programming language was developed, except for the vapor dispersion model. The results calculated using this program was carefully checked against those of consequence assessment examples in the ABSG study (FERC, 2004) to verify and validate the program. Unlike this study, the computations presented in the ABSG study were performed with the assistance of the Mathcad computer software.

4.1 LNG release process

Figures 3 and 4 show the influence of the breach diameter on the time taken to empty a tank above the waterline level and the time to vaporize all of the LNG released on water under the pool fire scenario and under the vapor dispersion scenario, respectively. In other words, the former time corresponds to total spill duration in both scenarios. The latter can be referred to as total fire duration in the pool fire scenario and as total evaporation duration in the vapor dispersion scenario.

The orifice model is used to calculate LNG release rate from a tank. Integrating Eq. (1) with the initial condition, $h = h_0$ at $t = 0$, one can easily obtain the analytical expression of the spill duration t_s as follows:

$$t_s = \sqrt{\frac{32h_0}{g}} \frac{A_t}{C_d\pi} d^{-2},$$

(10)

where d is the hole diameter, and h_0 and A_t depend on the size and capacity of an LNGC. Hence, as shown in Figs. 3 and 4, the total spill duration is depicted as a linear function of the breach diameter with a slope of -2 on a double logarithmic graph. On the other hand, the total duration of fire and that of evaporation can be obtained as a solution of the pool spread model. As for the total fire duration, it is equal to the total spill duration when the breach diameters are less than 2 and 3 m in Figs. 3(a) and 3(b), respectively. With the increase in the breach diameter, however, the curve representing the fire duration begins to deviate from the straight line representing the spill duration. The total spill duration is much shorter than the total fire duration when the breach diameters are larger than about 5 and 6 m for the conventional and latest LNGCs, respectively.

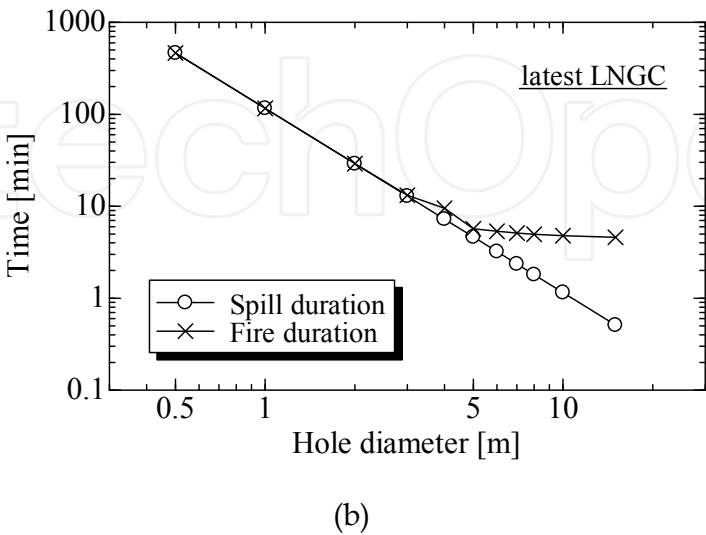
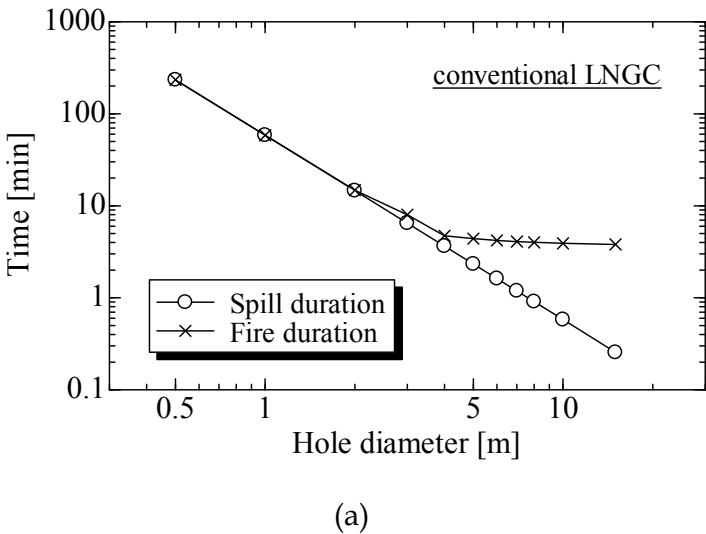


Fig. 3. Effect of breach diameter on the total duration of spill and that of fire under the pool fire scenario: (a) the conventional LNGC; (b) the latest LNGC.

From these findings, an LNG spill can be characterized as either a long duration release or a large-scale release of short duration, depending upon the breach diameter. In general, the former is referred to as a continuous spill, and the latter as an instantaneous spill. The instantaneous spill in the literal sense is unlikely to occur, and represents an ideal limiting case. In reality, it represents a large-scale spill for a short time. Under the present pool fire scenario, a release can be classified into the instantaneous spill type when the breach diameters are greater than about 5 and 6 m for the conventional and latest LNGCs, respectively. In the same manner, when the breach diameters are less than 2 and 3 m, respectively, it can be classified into the continuous spill type. Any release from a breach whose diameter lies between these two ranges is considered to be in transition from the continuous spill type to the instantaneous spill type.

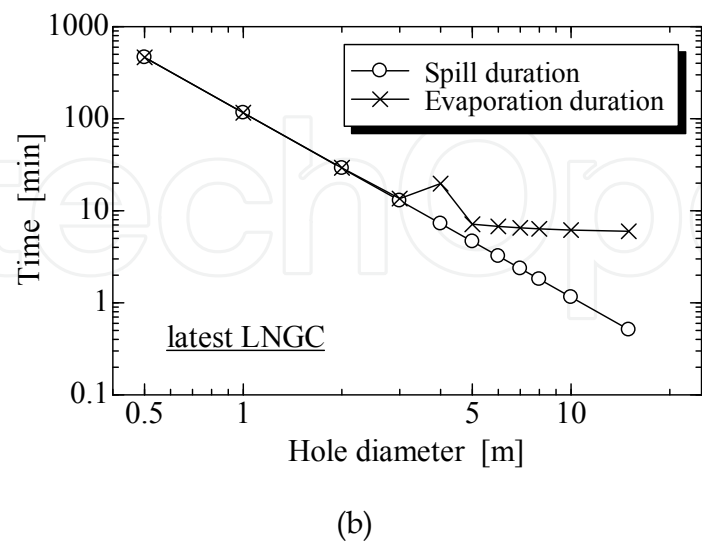
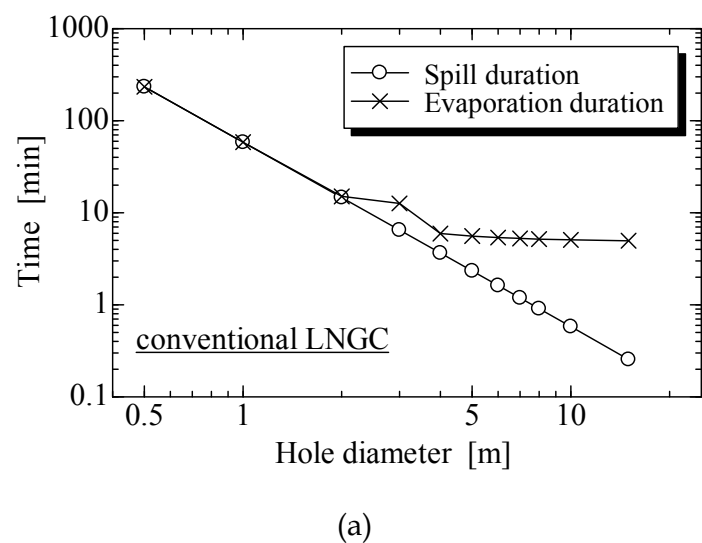


Fig. 4. Effect of breach diameter on the total duration of spill and that of evaporation under the vapor dispersion scenario: (a) the conventional size LNGC; (b) the latest LNGC.

On the Whole, the above discussion holds true for the total evaporation duration under the vapor dispersion scenario in Fig. 4. Unlike in Fig. 3, however, the curve representing the evaporation duration is markedly out of alignment in the transitional range between the continuous and instantaneous spill types. This is attributed to the difference of the vaporization rates of an LNG pool, i.e., the difference between the film boiling rate and the mass burning rate. The pool spread model recommended in the FERC method is based on an integral approach that can avoid the need to characterize a spill type as either instantaneous or continuous. However, the lack of smoothness of these duration data suggests that it is necessary to improve the pool spread model in view of the transitional spill type range.

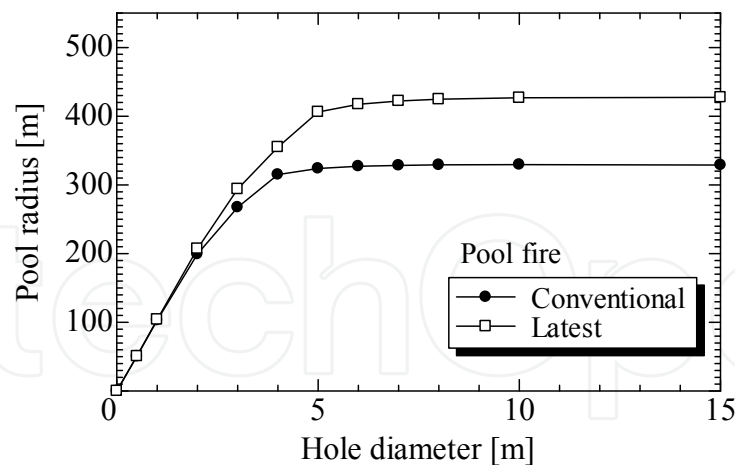
4.2 Pool spread process

Figures 5(a) and 5(b) show the sensitivity of the maximum pool radius to the breach size under the pool fire and vapor dispersion scenarios, respectively. In both scenarios the LNG pool radius increases with the increase in the breach diameter. Then, it reaches an asymptotic value when the breach diameters are greater than about 5 and 6 m for the conventional and latest LNGCs, respectively.

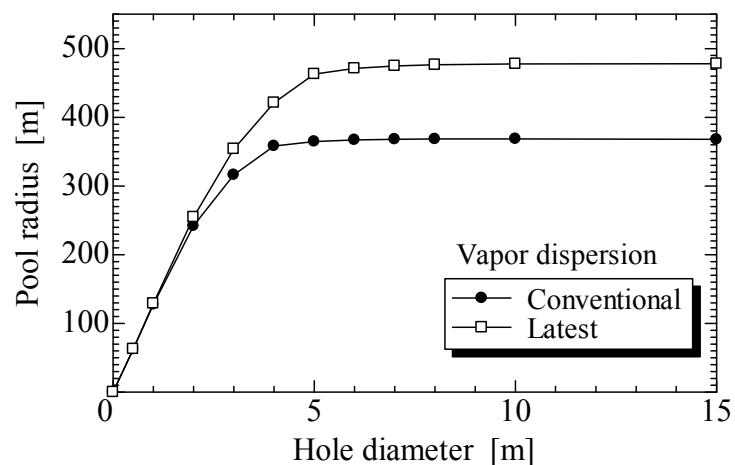
In the pool fire scenario, it can be seen from Figs. 3 and 5(a) that the maximum pool size is independent of the hole size in the instantaneous spill range. The asymptotic value for the latest LNGC is approximately 430 m, and is about 30 % longer than that for the conventional size. On the other hand, the maximum pool radius increases almost linearly in the continuous spill range. In particular, when the breach diameter is less than about 2 m, there is no significant difference of the maximum pool radius between the conventional and latest LNGCs. In this hole diameter range, the maximum pool radius can be approximately estimated on the assumption that the vaporization rate matches the release rate from a tank for most of the total spill duration.

The above discussion holds true for the results in the vapor dispersion scenario, except for the asymptotic value of a maximum pool radius. As shown in Fig. 5(b), it is approximately 480 m for the latest LNGC, and is longer than that in the case of the pool fire scenario because the vaporization rate is lower than the mass burning rate. Similarly to the pool fire case, the asymptotic value of the maximum pool radius for the latest type LNGC increases by 30 % as compared to the conventional type, whereas the spill volume doubles. The reason for this is as follows: The LNG release rates calculated by the orifice model are proportional to \sqrt{h} as shown in Eq. (1) and the initial height h_0 has almost the same value for the two size LNGCs, so that the release rates from the latest type LNGC are almost equal to those from the conventional type at the initial stage of a spill. Therefore, the maximum pool radius does not expand significantly even if the cargo capacity becomes twice as large (Oka & Ota, 2008).

In the present pool spread model, it is assumed that a single, semi-circular pool can be formed on water. In fact, however, the shape and size of the pool could be affected by environmental conditions, such as wind, waves and currents. Therefore, it may be more likely that the waves would break up a single pool into multiple irregular-shaped pools.



(a)



(b)

Fig. 5. Sensitivity of the maximum pool radius to the breach diameter under (a) the pool fire scenario and (b) the vapor dispersion scenario. The results for the conventional and latest LNGCs are compared in each scenario.

4.3 Pool fire process

For the conventional size LNGC, the sensitivity of the thermal radiation hazard distance to the breach diameter has already been investigated (Oka & Ota, 2008), but not for the latest one. Thus, the distances to 5 kW/m² are compared in Fig. 6 as a function of the hole diameter.

This intensity level is specified as a level of concern by the United States Federal Safety Standards for Liquefied Natural Gas Facilities (CFR, 1980). According to the Federal Safety Standards, the heat flux of 5 kW/m² is an acceptable level of concern for direct exposure of human beings. For bare skin exposure, a heat flux at this intensity level will result in unbearable pain after an exposure of 13 seconds and second degree burns after an exposure of 40 seconds (Mudan, 1984). In general, the intensity level of 5 kW/m² is used as a criterion for injury in a thermal radiation hazard assessment.

The downwind distance profiles shown in Fig. 6 are each calculated based on the maximum pool radii for its corresponding LNGC size, so that they give profiles similar to those of the LNG pool radii shown in Fig. 5(a). In the cases where breaches are less than 2 m in diameter, there is not much difference in the downwind distance between the two LNGC sizes, though the total volume spilled from the latest LNGC is twice that from the conventional size. The reason for this is that the LNG released from the tank is in the continuous spill range. When the breach diameters are greater than approximately 5 and 6 m for the conventional and latest LNGCs, respectively, the effect of the breach diameter on the thermal hazard distance is negligible. The asymptotic value of the downwind distance to 5 kW/m² extends approximately from 1,600 m up to 2,000 m due to the enlarged capacity of the latest LNGC. Consequently, while the spill volume doubles, the maximum thermal hazard distance for the latest LNGC increases by only 25 % than that for the conventional size because of the same reason as discussed in the previous section on the pool spread process.

The present study assumes that a single, coherent pool fire can be maintained for a very large pool diameter. However, this assumption may not be appropriate due to the inability of air to reach the interior of a fire and maintain combustion over such a large LNG pool (Luketa-Hanlin, 2006). Instead, the flame envelope would break up into several smaller, shorter flames at some very large size due to the environmental conditions, such as wind, waves and currents. The SNL study (Hightower et al., 2004) noted that these factors could reduce the thermal hazard distance by a factor of two to three. However, it is not yet known how to determine the limiting breakup diameter for a given LNG pool fire on water. The pool diameters presented here are speculative because experiments for large pool fires have never been performed (Luketa-Hanlin, 2006; Raj, 2007). Therefore, due to the assumption of a single, coherent pool fire, the hazard distances obtained in the present analyses should rather be considered as conservative estimates.

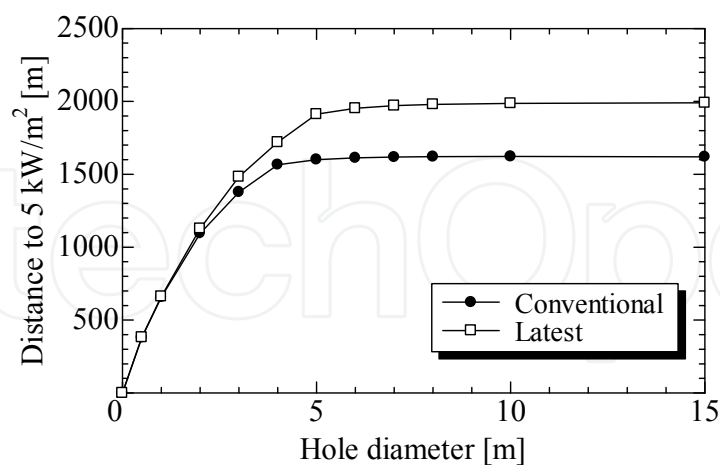


Fig. 6. Sensitivity of the downwind distance to 5 kW/m² to the hole diameter of a single tank for the conventional and latest LNGCs.

4.4 Vapor cloud dispersion process

For flammable vapor dispersion distance calculation, the level of concern is generally taken as the LFL for the substance in the case of a flash fire. In addition, the level of concern is often defined as half the LFL to account for the localized pockets of higher gas concentrations that may occur in an actual release. The use of half the LFL for LNG is also supported by the Federal Safety Standards (CFR, 1980), which specifies the use of an average gas concentration in air of 2.5 % for onshore exclusion zones. For the present calculations, hazard distances are provided for the LFL.

Figure 7 shows the effect of the hole diameter on the maximum distance to the LFL. The dispersion calculations were conducted under atmospheric stability class F as the worst-case scenario. Similarly to the calculation of the pool radius and the thermal hazard distance, profiles of the distance to reach the LFL are given as a function of the hole diameter, and it reaches an asymptotic value with the increase in the breach diameter. However, unlike the pool spread and pool fire processes, the vapor dispersion distance approaches asymptotically to an averagely constant level when the breach diameters are greater than about 3 and 4 m for the conventional and latest LNGCs, respectively. This inconsistency is attributed to the total evaporation duration which is singularly longer in the transitional spill range, as shown in Fig. 4. The asymptotic value of the distance to the LFL for the latest LNGC is only about 30 % longer than that for the conventional size, while the total spill volume from the latest LNGC is twice as much. This reason is the same as elaborated in the pool spread process.

From the above discussion, it has been found that the evolution of an LNG vapor cloud is strongly influenced by the characteristics of the LNG pool spread process, i.e., the source conditions. This fact is consistent with the dispersion behavior of denser-than-air gas observed in field experiments (Blackmore et al., 1982). Therefore, it is necessary to improve the present pool spread model so as to provide more accurate source conditions for vapor dispersion calculation.

As mentioned earlier in the first section, Qiao et al. investigated the sensitivity of vapor dispersion consequences to the breach diameter for the conventional size LNGC using the FERC method (Qiao et al., 2006). In their study, the averaging time to estimate flammable gas concentrations was set to 1 minute, though the use of a much shorter period of time was recommended in the FERC method (see Table 1). In the vapor dispersion scenarios of the ABSG study (ABSG, 2004; FERC, 2004), the averaging time was set to 0 second, so that the same averaging time is also used in this study. Qiao et al. employed completely the same scenarios as those in the ABSG study, which provided results of two example dispersion calculations (FERC, 2004). The downwind distances to the LFL shown in the ABSG study were about 3,400 and 4,100 m for 1 m and 5 m hole diameters, respectively, whereas the corresponding results by Qiao et al. were about 3,400 and 3,300 m. Their results are in contradiction to the previous experimental observation that the higher the vaporization rate is, the greater the distance to the LFL becomes. In addition, they performed curve fitting for their calculated values without taking account of the results in the cases where the hole diameters were 1, 4 and 6 m. Nevertheless, they drew a questionable conclusion that the distance to the LFL approached asymptotically to an almost constant level when the breach diameter was greater than 5 m for the conventional size LNGC.

Finally, the present results are briefly compared to those in the ABSG study (FERC, 2004). When the hole diameters are 1 and 5 m, the distances to the LFL in this study are about 3,340

and 4,940 m for the conventional size LNGC, respectively. Since the LNG spill volume in the present calculation is greater than that in the ABSG study, both results are not compared quantitatively in a strict sense. In addition, for the purpose of conservative estimation, the maximum distances are determined by the LFL concentrations at the ground level, in contrast to a default height of 0.5 m to calculate the flammability contours in DEGADIS. In the case with 1 m hole diameter, however, almost the same results are obtained in both of the studies, because the release is in the continuous spill range. On the other hand, since the LNG release from a hole with a diameter of 5 m is classified into the instantaneous spill type, the dispersion distance in the present study is longer than that in the ABSG study due to the effects of the larger spill volume and the difference of the elevation level to measure the LFL concentration.

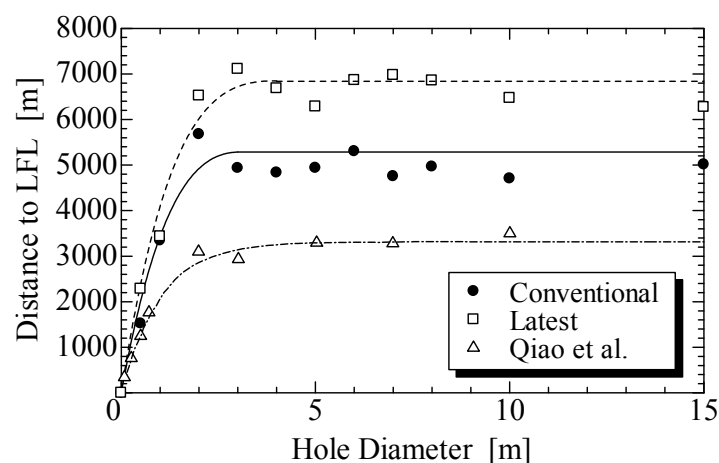


Fig. 7. Sensitivity of the downwind distance to the LFL to the hole diameter of a single tank for the conventional and latest LNGCs. For comparison, results from the previous study (Qiao et al., 2006) are also shown in the figure.

5. Concluding remarks

Consequence analyses of large-scale liquefied natural gas spills on water have been carried out using the method proposed by the Federal Energy Regulatory Commission (FERC, 2004). The principal LNG hazards of interest for the present study are those posed by thermal radiation and flammable vapor dispersion following unconfined LNG spills on water. In particular, this study has focused on the sensitivity of the LNG release duration, of the volatile pool spread, and of the pool fire and vapor dispersion hazards to the size of a hole breached in a membrane-type tank of the conventional and latest LNGCs. From the practical viewpoint of applicability to any breach size, the use of the FERC models has been recommended as the most appropriate, practical method at the present time (Oka & Ota, 2008; Oka, 2009).

The present sensitivity analyses have shown that the consequences are strongly dependent upon the breach size in the ranges associated with the continuous and transitional spill types under the present release assumption. On the other hand, when the breach diameter is

larger than a certain critical value, there is little influence on the consequences regardless of the scenarios of pool fire and vapor dispersion hazards.

In the pool fire scenario, the critical values of the hole diameter are about 5 and 6 m for the conventional and latest LNGCs, respectively. In the vapor dispersion scenario, on the other hand, the critical diameters for the distance to the LFL are approximately 3 and 4 m for the two size LNGCs, respectively. This inconsistency is attributed to the singularly long evaporation duration of an LNG pool in the transitional spill range. These singular solutions obtained from the pool spread model indicate the lack of appropriate dynamic nature for transitional spills in the present integral approach.

Therefore, it is important to develop a simple, but accurate pool spread model without dependence on spill types. On the other hand, it should be noted that practical consequence assessment methods can generally provide only rough estimates of the magnitude of effects for incidents involving large LNG release on water because of the variability in actual incident circumstances as well as the uncertainty inherent in the methods used.

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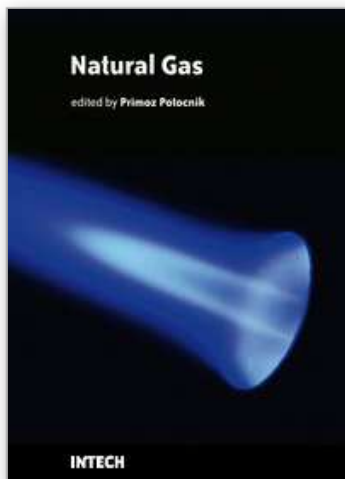
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The contributions in this book present an overview of cutting edge research on natural gas which is a vital component of world's supply of energy. Natural gas is a combustible mixture of hydrocarbon gases, primarily methane but also heavier gaseous hydrocarbons such as ethane, propane and butane. Unlike other fossil fuels, natural gas is clean burning and emits lower levels of potentially harmful by-products into the air. Therefore, it is considered as one of the cleanest, safest, and most useful of all energy sources applied in variety of residential, commercial and industrial fields. The book is organized in 25 chapters that cover various aspects of natural gas research: technology, applications, forecasting, numerical simulations, transport and risk assessment.

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